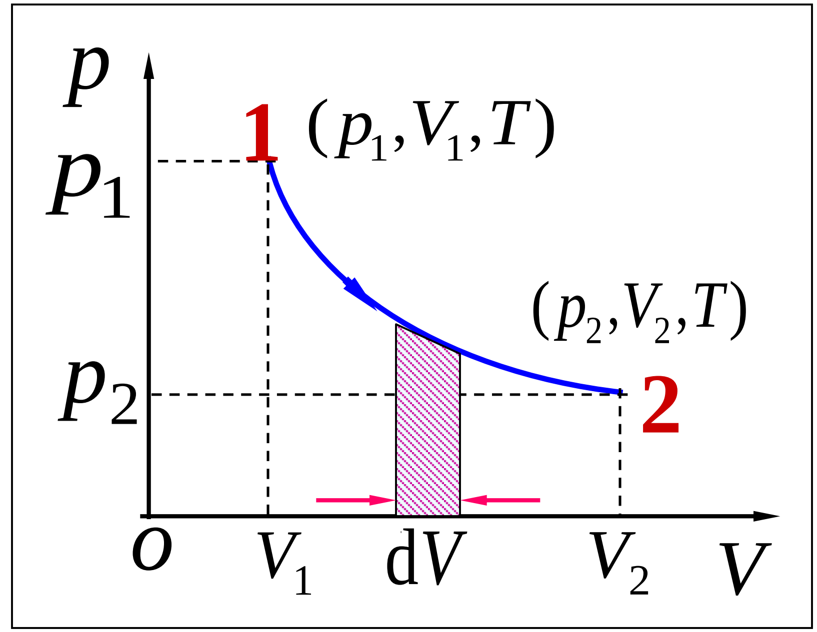
一 等温过程

特征 $T=$ 常量

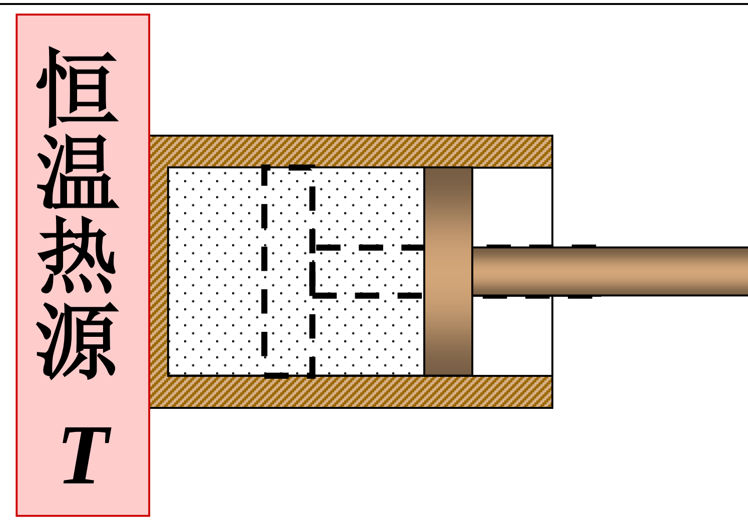
过程方程 $pV=$ 常量

$$\mathrm{d}E=0$$



由热力学第一定律

$$\mathrm{d}Q_T=\mathrm{d}W=p\mathrm{d}V$$

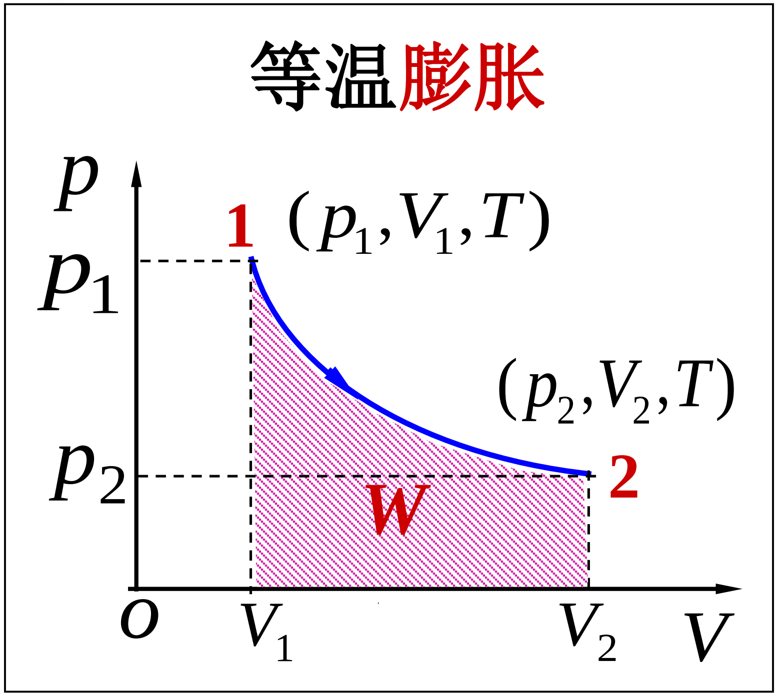


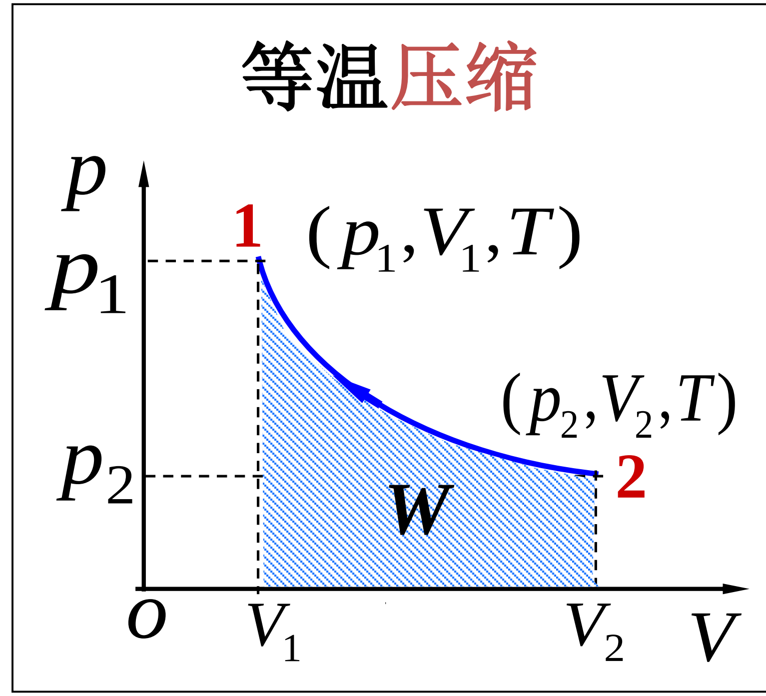
13-4 理想气体的等温过程和绝热过程

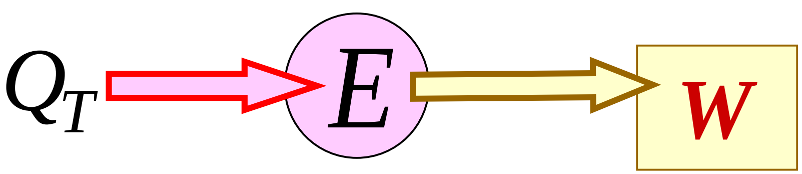
$$Q_T = W = \int_{V_1}^{V_2} p\mathrm{d}V$$

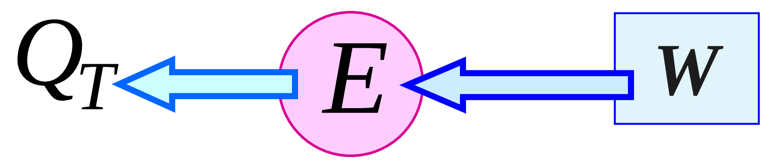
$$p = \nu \frac{RT}{V}$$

$$Q_T = W = \int_{V_1}^{V_2} \nu \frac{RT}{V}\mathrm{d}V \boxed{= \nu RT \ln \frac{V_2}{V_1}}$$


等温膨胀
p
1 (p_1,V_1,T)
p_1
(p_2,V_2,T)
p_2
2
W
O
V_1
V_2
V


等温压缩
p
1 (p_1,V_1,T)
p_1
(p_2,V_2,T)
p_2
2
W
O
V_1
V_2
V


Q_T
E
W


Q_T
E
W

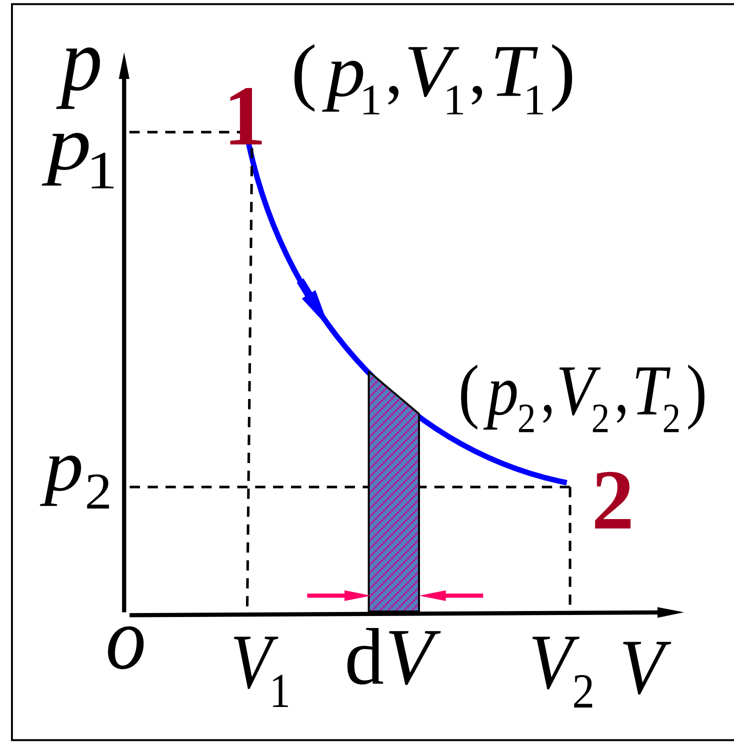
二　绝热过程

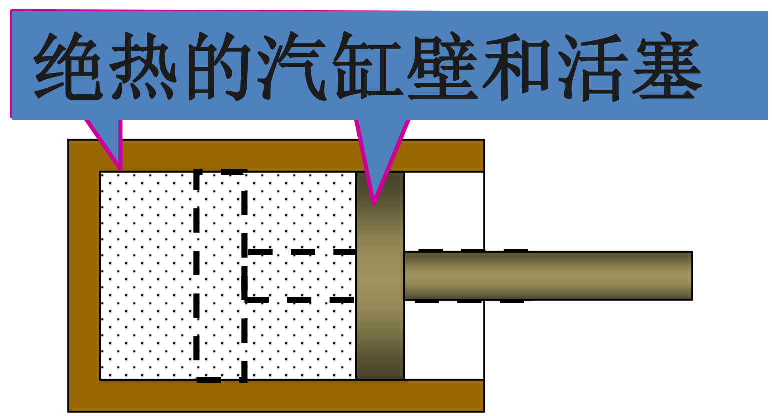
与外界无热量交换的过程

特征　　$dQ = 0$

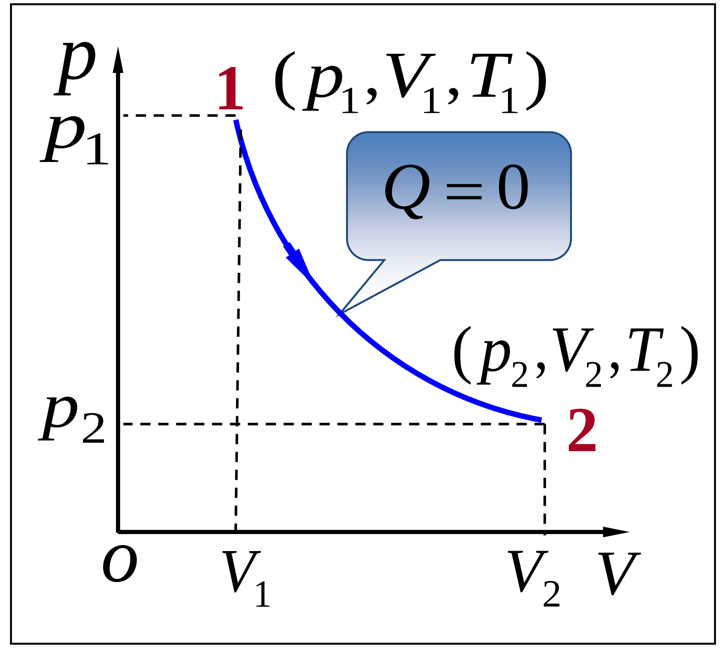
过程方程　$pV^{\gamma} = C$

绝热方程	
	$V^{\gamma-1}T =$ 常量
	$pV^{\gamma} =$ 常量
	$p^{\gamma-1}T^{-\gamma} =$ 常量





绝热过程方程的推导



$$\because \mathrm{d}Q = 0, \quad \therefore \mathrm{d}E + \mathrm{d}W = 0$$

$$\nu C_{V,\mathrm{m}} \mathrm{d}T + p\mathrm{d}V = 0$$

$$pV = \nu RT$$

$$p\mathrm{d}V + V\mathrm{d}p = \nu R\mathrm{d}T$$

$$C_{V,m}(p\mathrm{d}V + V\mathrm{d}p) + R \cdot p\mathrm{d}V = 0$$

$$C_{p,m} p\mathrm{d}V + C_{V,m} V\mathrm{d}p = 0 \qquad \gamma p\mathrm{d}V + V\mathrm{d}p = 0$$

$$\gamma \frac{\mathrm{d}V}{V} + \frac{\mathrm{d}p}{p} = \mathrm{d}(\ln pV^{\gamma}) = 0 \qquad \boxed{pV^{\gamma} = C}$$

绝热过程的功

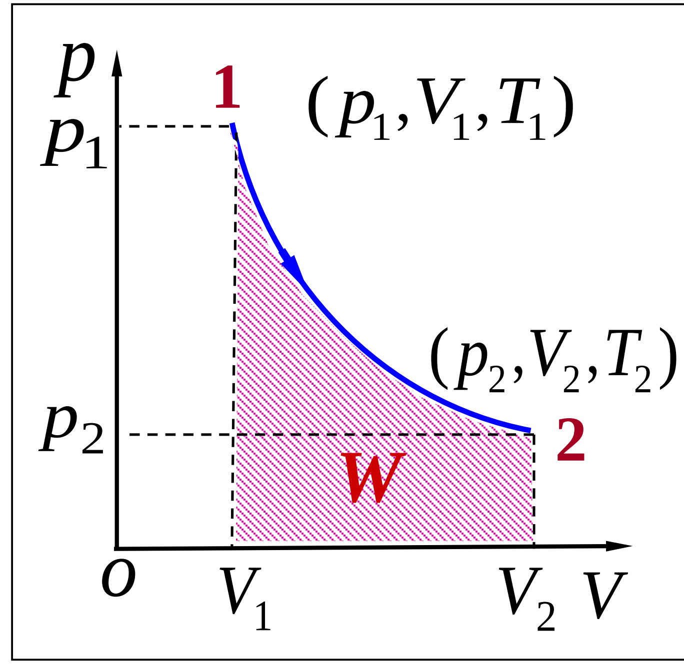
由热力学第一定律有 $Q=\Delta E+W=0$

$$W=-\Delta E=\nu C_{V,\mathrm{m}}(T_1-T_2)$$

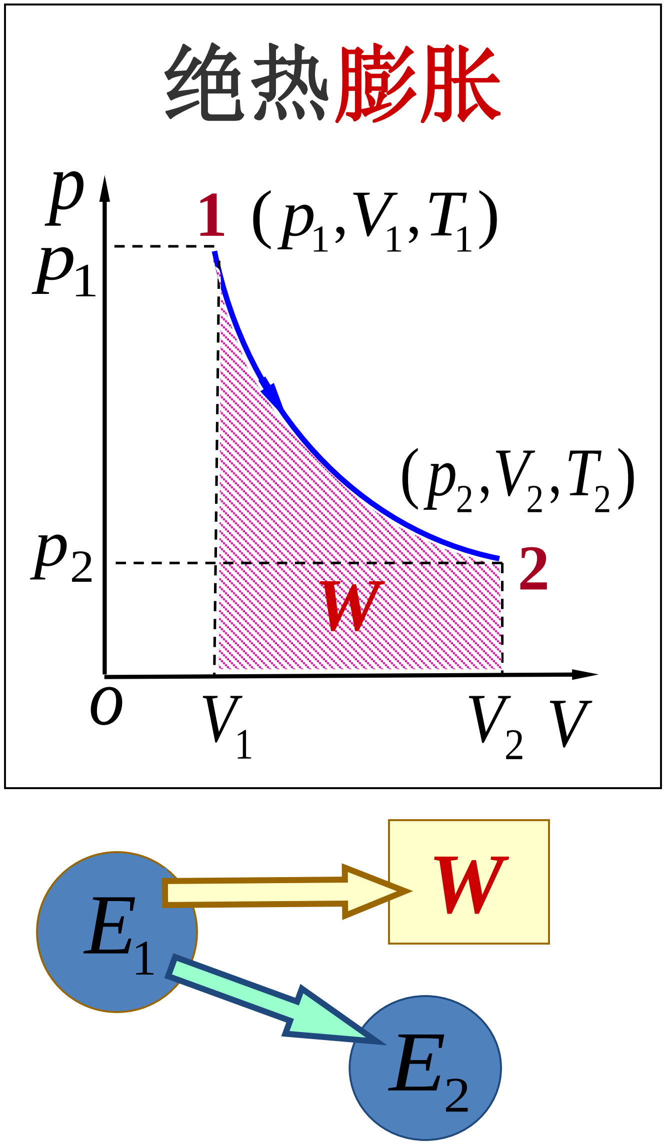
由 $pV=\nu RT$ 可得

$$W=C_{V,\mathrm{m}}\left(\frac{p_1V_1}{R}-\frac{p_2V_2}{R}\right)$$

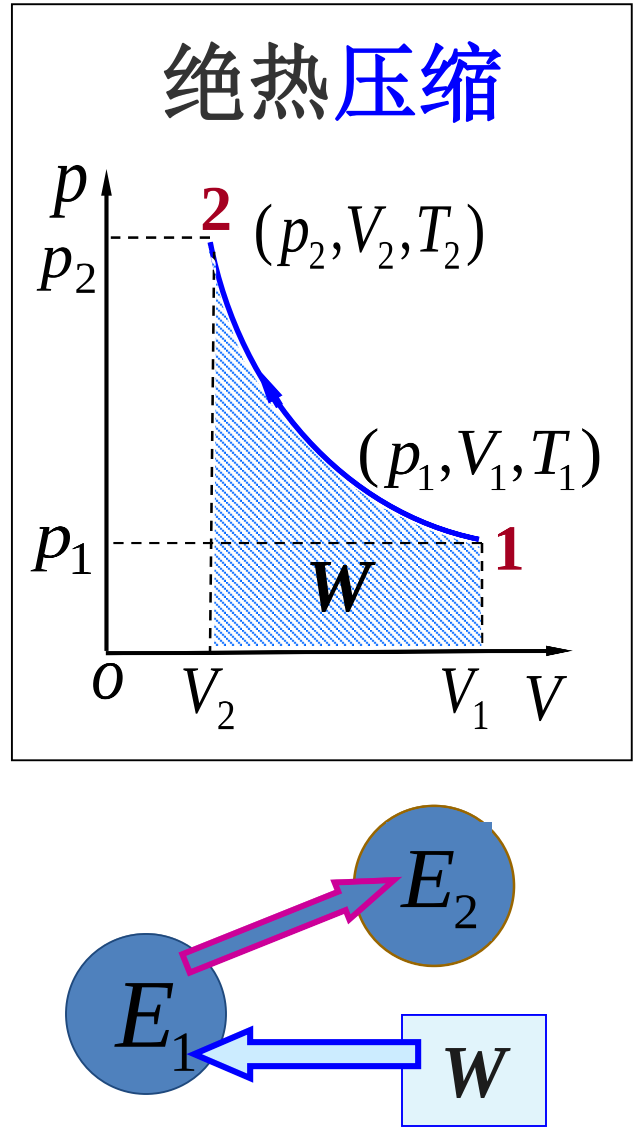
$$=\frac{C_{V,\mathrm{m}}}{C_{p,\mathrm{m}}-C_{V,\mathrm{m}}}(p_1V_1-p_2V_2)$$



$$\boxed{W=-\frac{p_2V_2-p_1V_1}{\gamma-1}}$$



绝热膨胀
p
p_1
$1\ (p_1,V_1,T_1)$
(p_2,V_2,T_2)
p_2
2
W
O
V_1
V_2
V
E_1
W
E_2



绝热压缩
p
p_2
$2\ (p_2,V_2,T_2)$
(p_1,V_1,T_1)
p_1
1
W
O
V_2
V_1
V
E_2
E_1
W

三 绝热线和等温线

绝热过程曲线的斜率

$$pV^{\gamma}=常量$$

$$\gamma pV^{\gamma-1}\mathrm{d}V+V^{\gamma}\mathrm{d}p=0$$

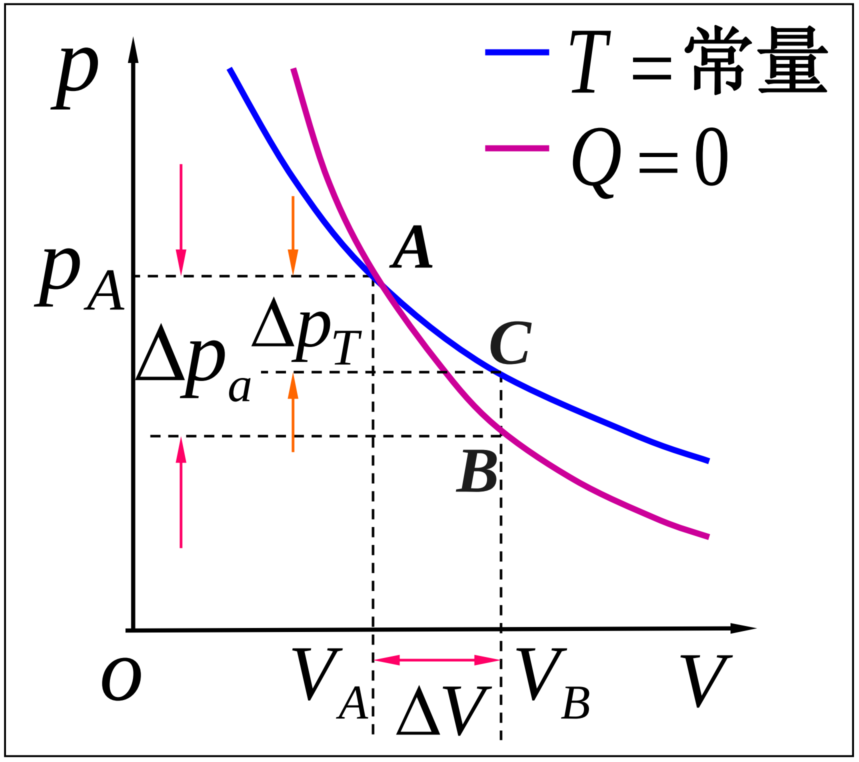
$$(\frac{\mathrm{d}p}{\mathrm{d}V})_{a}=-\gamma\frac{p_{A}}{V_{A}}$$

等温过程曲线的斜率

$$pV = 常量$$

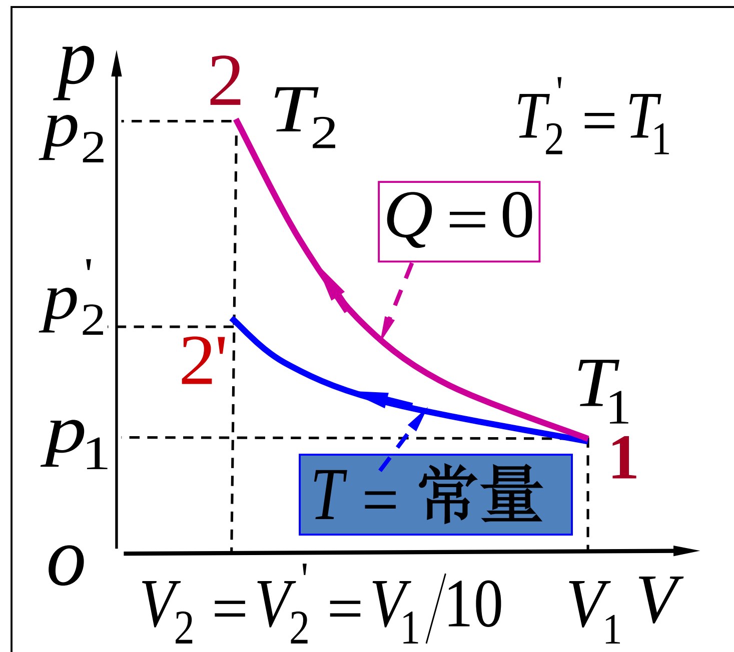
$$p\mathrm{d}V + V\mathrm{d}p = 0$$

$$\left(\frac{\mathrm{d}p}{\mathrm{d}V}\right)_T = -\frac{p_A}{V_A}$$



绝热线的斜率大于等温线的斜率.

例1 设有 5 mol 的氢气，最初温度 $20^{\circ}\mathrm{C}$，压强 $1.013\times10^{5}\,\mathrm{Pa}$，求下列过程中把氢气压缩为原体积的 1/10 需作的功：（1）等温过程（2）绝热过程（3）经这两过程后，气体的压强各为多少？



已知： $\nu = 5\ \mathrm{mol}\quad T_0 = 293\ \mathrm{K}$

$$P_0 = 1.013\times 10^5\ \mathrm{Pa}\quad V = 0.1V_0$$

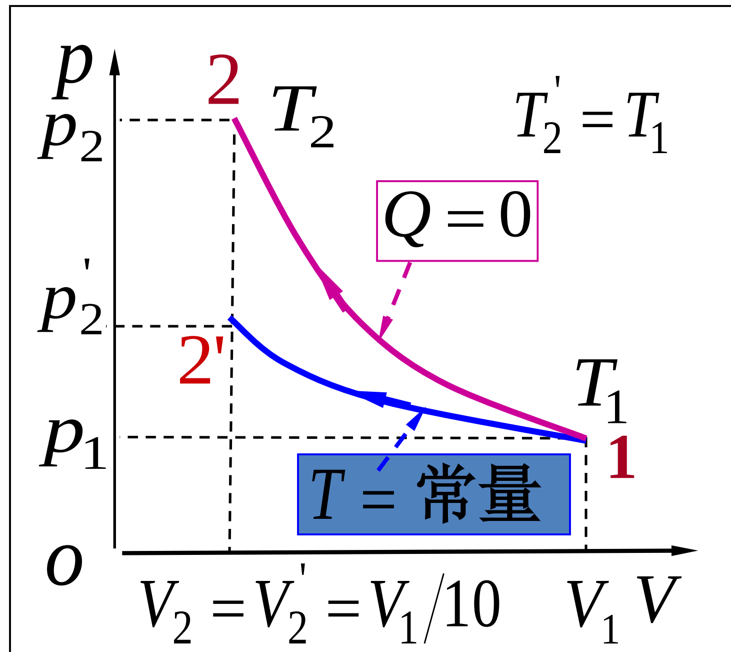
解 （1）等温过程

$$W_{12}' = \nu RT\ln\frac{V_2'}{V_1} = -2.80\times 10^4\ \mathrm{J}$$

（2）氢气为双原子气体

由表查得$\gamma = 1.41$，有

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1} = 753\ \mathrm{K}$$



$$W_{12}=-\nu C_{V,m}(T_2-T_1)\qquad C_{V,m}=20.44\ \mathrm{J\cdot mol^{-1}\cdot K^{-1}}$$

$$W_{12}=-4.70\times10^4\ \mathrm{J}$$

（3）对等温过程

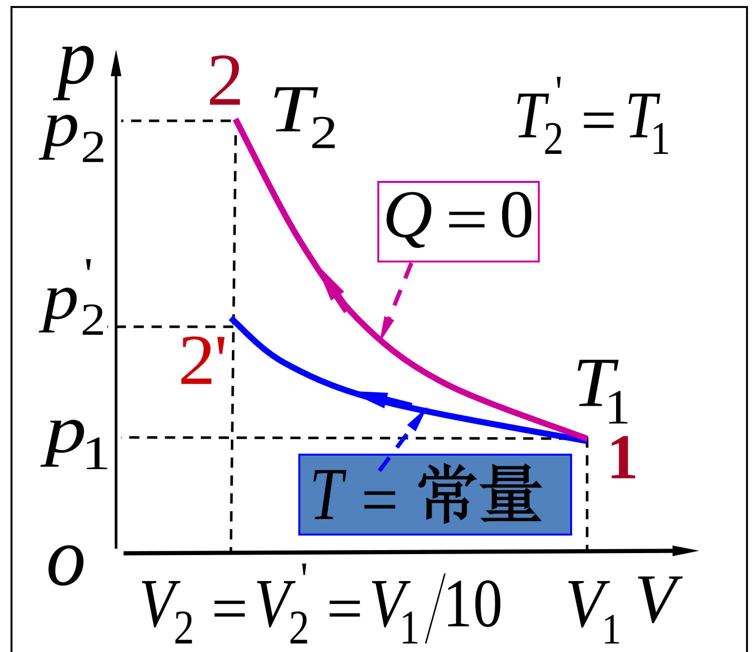
$$p_2'=p_1\left(\frac{V_1}{V_2}\right)$$

$$=1.01\times10^6\ \mathrm{Pa}$$

对绝热过程，有

$$p_2=p_1\left(\frac{V_1}{V_2}\right)^{\gamma}$$

$$=2.55\times10^6\ \mathrm{Pa}$$



四、多方过程(polytropic process)

$$C_{n.m}=Const.$$

多方过程方程： $pV^{n}=C$

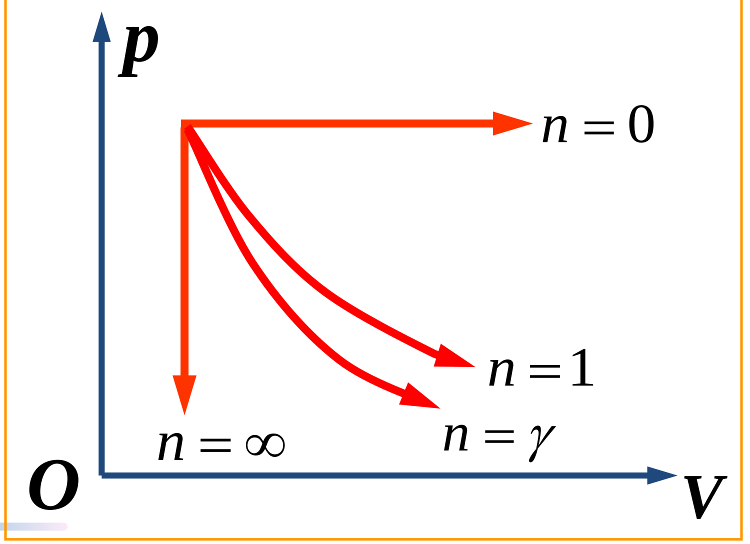
$$\text{其中}\, n=\frac{C_{n,m}-C_{p,\mathrm{m}}}{C_{n,m}-C_{V,\mathrm{m}}}\,\text{为多方指数}$$

等压过程： $\mathrm{d}p=0$ $n=0$

等体过程: $\mathrm{d}V=0$ $n\to\infty$

等温过程： $\mathrm{d}T=0$ $n=1$

绝热过程： $Q=0$ $n=\gamma$



- 计算多方**过程**的功。

$$pV^n = C \qquad p = CV^{-n}$$

$$W = \int p dV = \int CV^{-n} dV = \frac{1}{-n+1}\int dV^{-n+1}$$

$$W = \frac{C}{1-n}(V_f^{1-n} - V_i^{1-n}) \qquad C = p_f V_f^n = p_i V_i^n$$

$$W = -\frac{1}{n-1}(p_f V_f - p_i V_i) \qquad pV = \nu RT$$

$$W = -\frac{\nu R}{n-1}\Delta T \qquad dW = \nu\frac{R}{1-n}dT$$

- 多方过程的热容量 $\mathrm{d}Q_n = \nu C_{n,\mathrm{m}}\mathrm{d}T$

$$dE = \nu\frac{i}{2}RdT = \nu C_{V,m}dT \quad dW = \nu\frac{R}{1-n}dT$$

$$\mathrm{d}Q = \mathrm{d}E + \mathrm{d}W$$

$$C_{n,\mathrm{m}} = C_{V,\mathrm{m}} + \frac{R}{1-n} \qquad C_{p,\mathrm{m}} = C_{V,\mathrm{m}} + R$$

$$C_{n,\mathrm{m}} = C_{V,\mathrm{m}} + \frac{C_{p,m} - C_{V,m}}{1-n} \qquad \gamma = C_{p,\mathrm{m}}/C_{V,\mathrm{m}}$$

$$C_{n,\mathrm{m}} = C_{V,\mathrm{m}}(1+\frac{\gamma-1}{1-n}) = \frac{\gamma-n}{1-n}C_{V,\mathrm{m}}$$

一、热力学循环过程

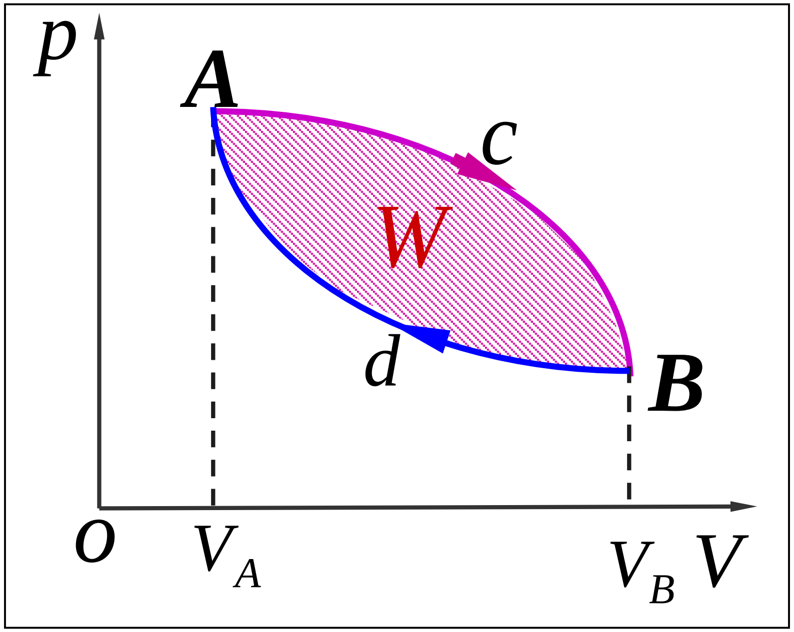
1、循环过程

系统经过一系列变化状态过程后，又回到原来的状态的过程叫热力学循环过程．

特征 $\Delta E = 0$

由热力学第一定律

$$Q = W$$



净功 $W = Q_1 - \boxed{Q_2} = Q$

总吸热 $\longrightarrow Q_1$

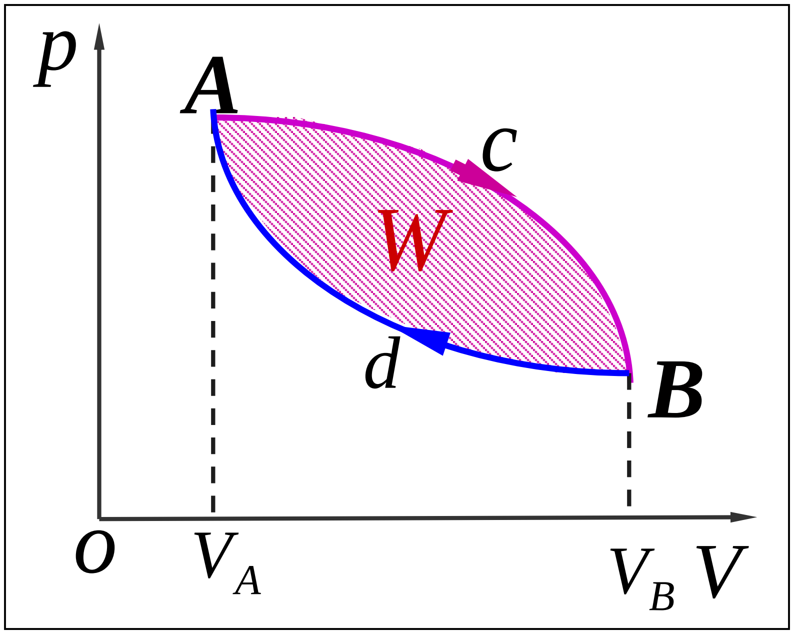
总放热 $\longrightarrow Q_2$ （取绝对值）

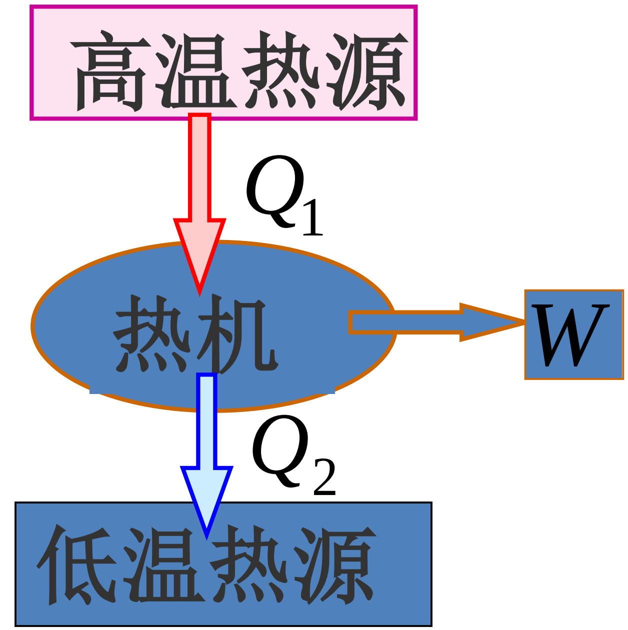
净吸热 $\longrightarrow Q$

2 热机效率和致冷机的致冷系数

热机（正循环） $W > 0$

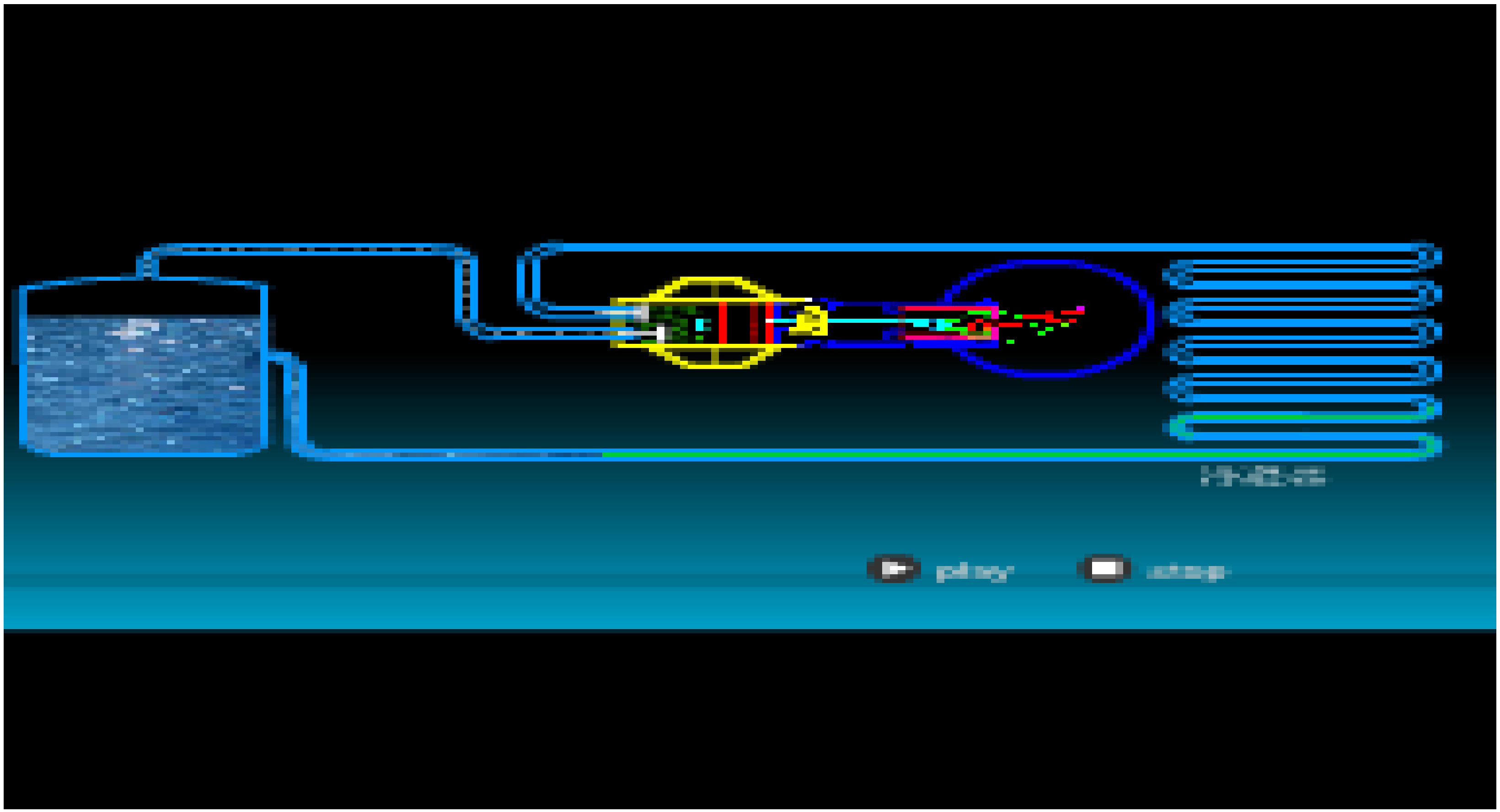
致冷机（逆循环） $W < 0$





热机效率 $\eta = \dfrac{W}{Q_1} = \dfrac{Q_1 - Q_2}{Q_1} = 1 - \dfrac{\boxed{Q_2}}{Q_1}$

热机：持续地将热量转变为功的机器 .



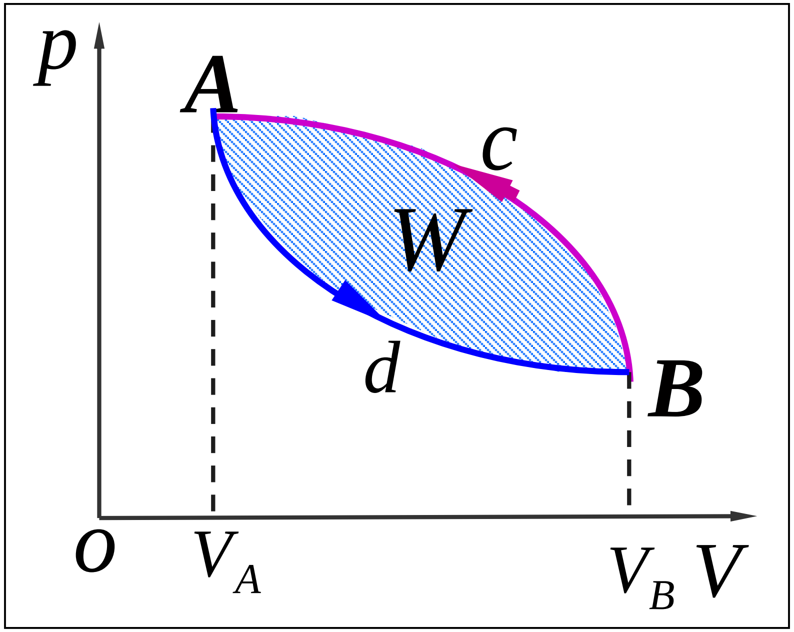
各种热机的效率

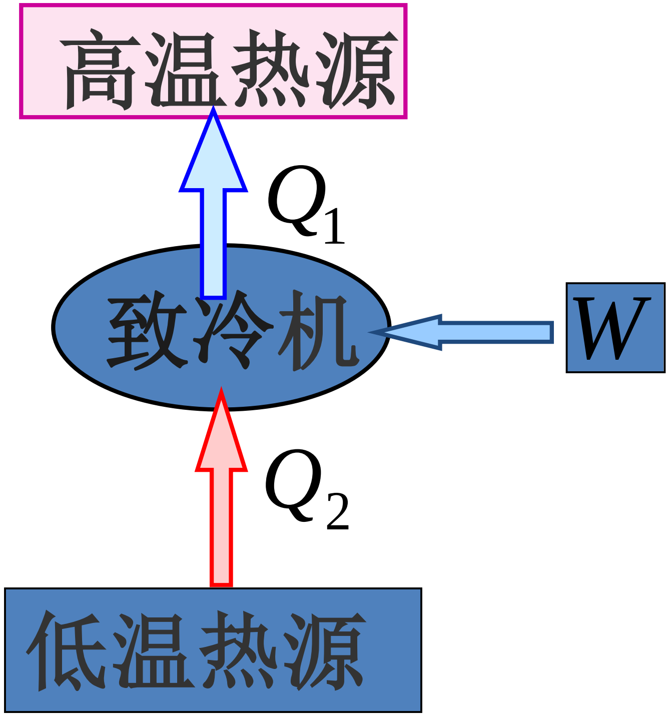
液体燃料火箭 $\eta = 48\%$

柴油机 $\eta = 37\%$

汽油机 $\eta = 25\%$

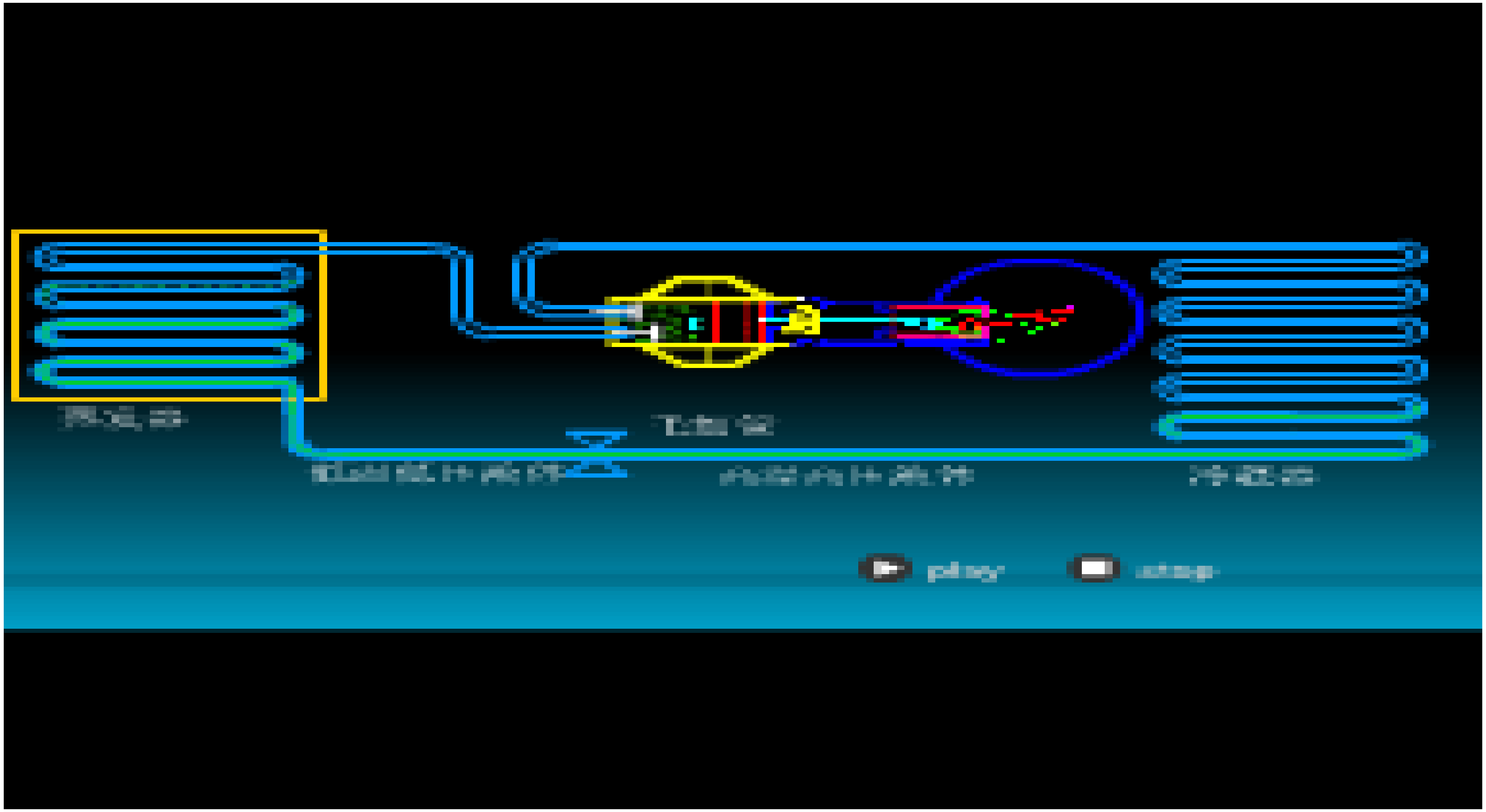
蒸汽机 $\eta = 8\%$





致冷机致冷系数 $$e=\frac{Q_2}{|W|}=\frac{Q_2}{\boxed{Q_1}-Q_2}$$

冰箱循环示意图



三 卡诺循环

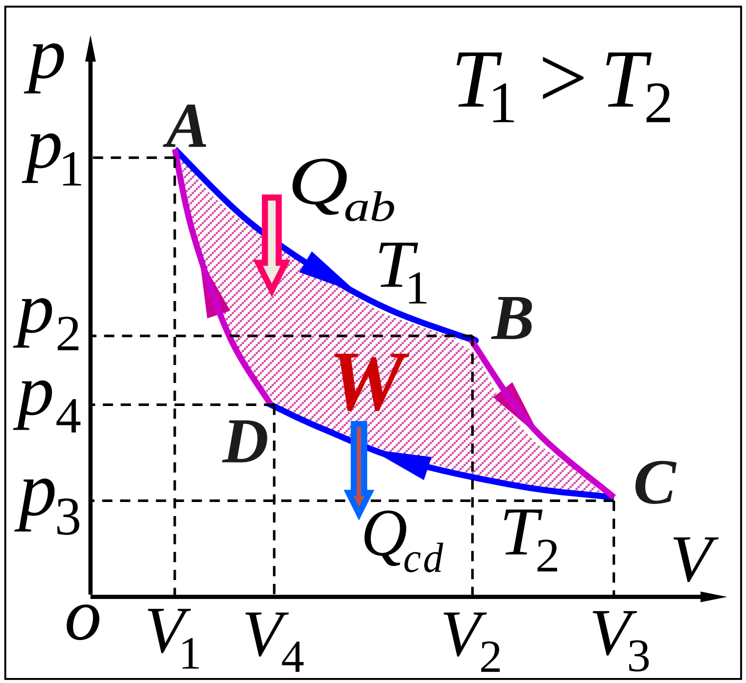
1698年萨维利和1705年纽可门先后发明了蒸汽机，当时蒸汽机的效率极低．1765年瓦特进行了重大改进，大大提高了效率．

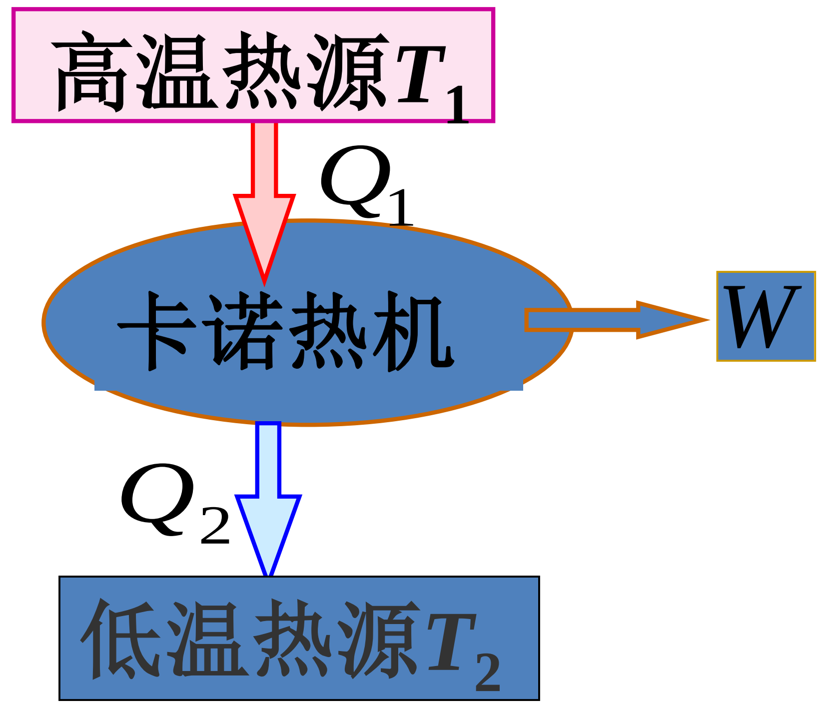
1824 年法国的年青工程师卡诺提出一个工作在两热源之间的理想循环—卡诺循环. 给出了热机效率的理论极限值；他还提出了著名的卡诺定理.

卡诺循环由两个等温过程和两个绝热过程组成 .

A — B 等温膨胀　　B — C 绝热膨胀

C — D 等温压缩　　D — A 绝热压缩



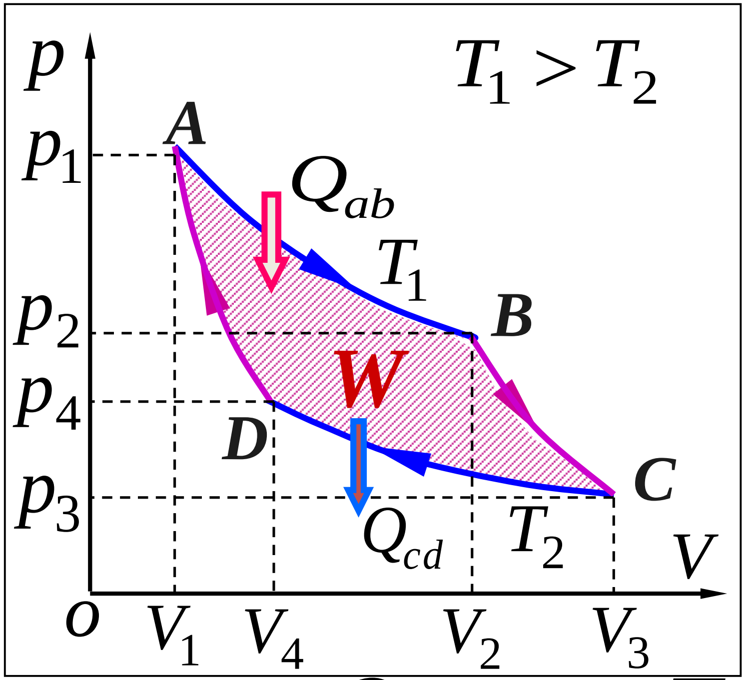


A — B 等温膨胀吸热

$$Q_1 = Q_{ab} = \nu R T_1 \ln \frac{V_2}{V_1}$$

C — D 等温压缩放热

$$Q_2 = |Q_{cd}| = \nu R T_2 \ln \frac{V_3}{V_4}$$



B — C 绝热过程

$$T_1 V_2^{\gamma-1} = T_2 V_3^{\gamma-1}$$

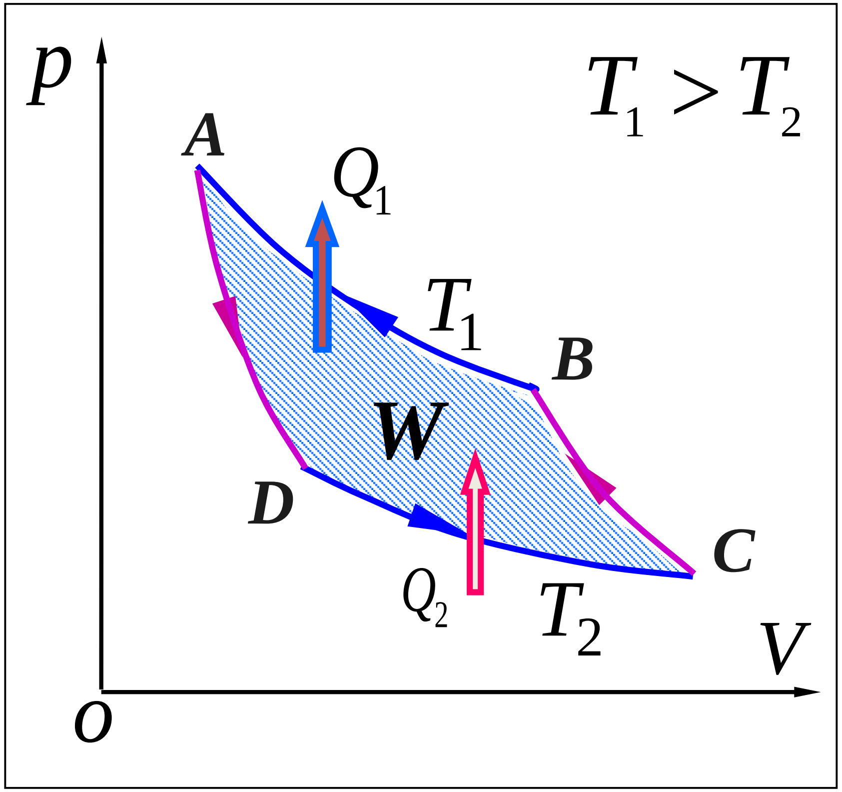
D — A 绝热过程

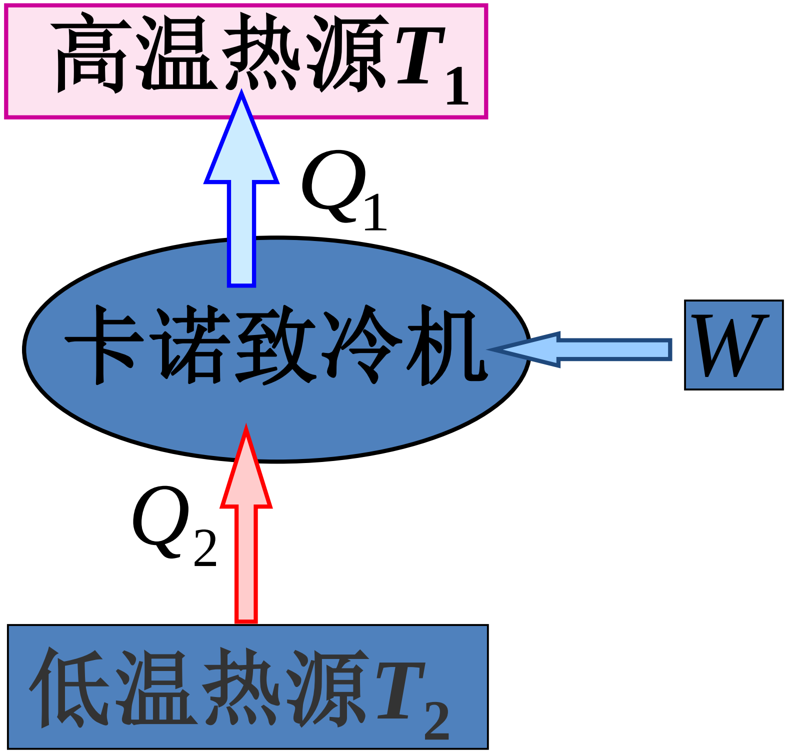
$$T_1 V_1^{\gamma-1} = T_2 V_4^{\gamma-1}$$

$$\frac{V_2}{V_1} = \frac{V_3}{V_4}$$

$$\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$$

卡诺致冷机（卡诺逆循环）



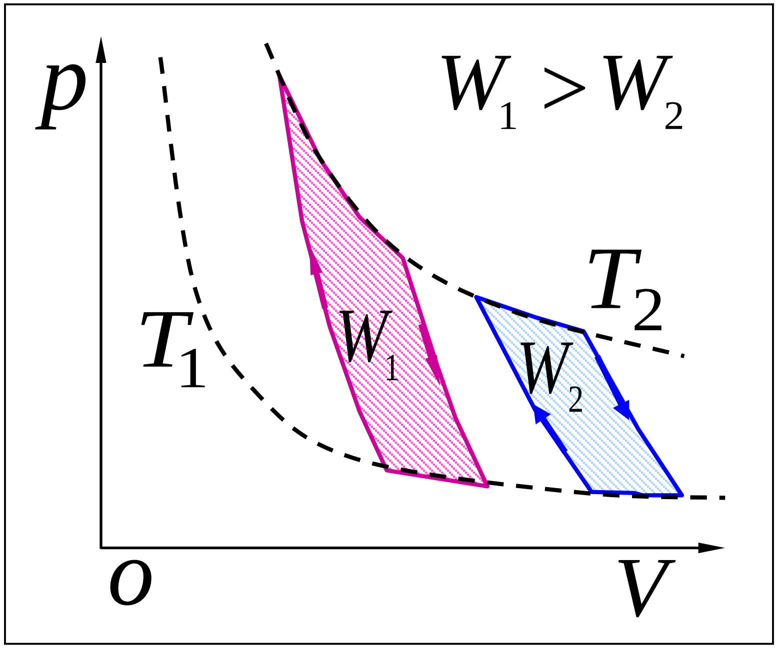


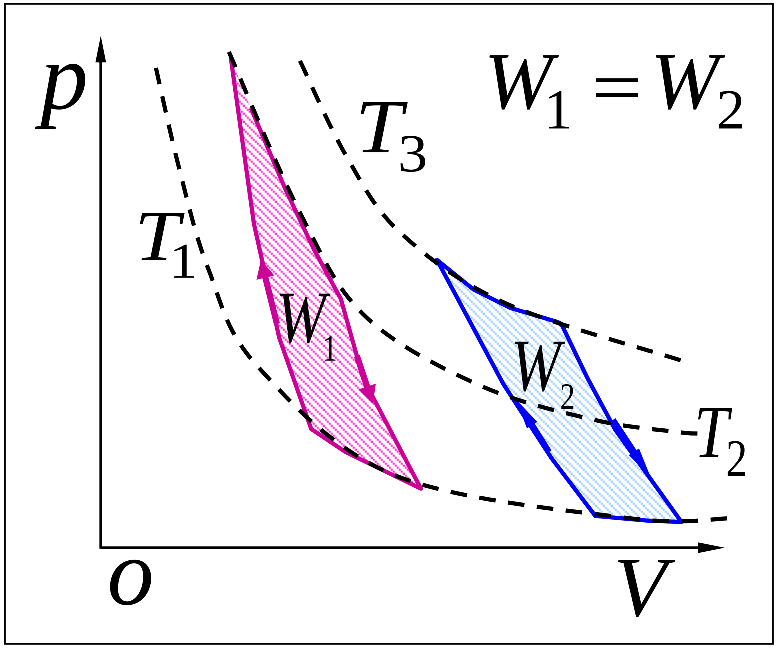
卡诺致冷机致冷系数

$$e = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

讨 论

图中两卡诺循环 $\eta_1 = \eta_2$ 吗 ?





$\eta_1 = \eta_2$

$\eta_1 < \eta_2$

例2 一电冰箱放在室温为 $20^{\circ}\mathrm{C}$ 的房间里，冰箱储藏柜中的温度维持在$5^{\circ}\mathrm{C}$. 现每天有 $2.0\times10^{7}\,\mathrm{J}$ 的热量自房间传入冰箱内，若要维持冰箱内温度不变，外界每天需作多少功，其功率为多少？设在$5^{\circ}\mathrm{C}$ 至 $20^{\circ}\mathrm{C}$ 之间运转的冰箱的致冷系数是卡诺致冷机致冷系数的 55%.

解
$$e=e_{\text{卡}}\times 55\%=\frac{T_2}{T_1-T_2}\times\frac{55}{100}=10.2$$

由 $e=\dfrac{Q_2}{Q_1-Q_2}$ 得 $Q_1=\dfrac{e+1}{e}Q_2$

房间传入冰箱的热量 $Q'=2.0\times10^7\ \mathrm{J}$

热平衡时 $Q'=Q_2$

$$Q_1=\frac{e+1}{e}Q_2=\frac{e+1}{e}Q'=2.2\times10^7\ \mathrm{J}$$

保持冰箱在 $5^\circ\mathrm{C}$ 至 $20^\circ\mathrm{C}$ 之间运转，每天需作功

$$W = Q_1 - Q_2 = Q_1 - Q' = 0.2\times10^7\ \mathrm{J}$$

功率 $$P = \frac{W}{t} = \frac{0.2\times10^7}{24\times3600}\ \mathrm{W} = 23\ \mathrm{W}$$

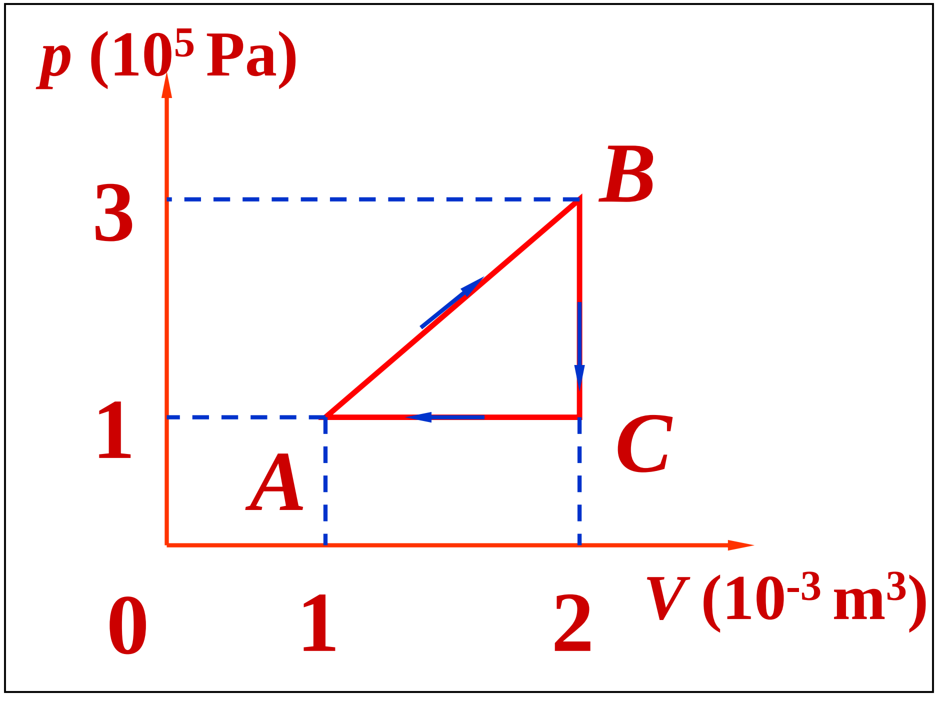
2、 摩尔数为ν=1的单原子分子理想气体，从初态A出发，经历如图循环过程，求:

（0）分别确定三个端点的状态参量(P, V, T, E)。分别在P-T图和V-T图上化出循环过程。

（1）各过程系统作功W、内能变化ΔE、吸热量Q和摩尔热容.

（2）整个循环过程系统对外作的总功及净吸热.

（3）该循环的效率.



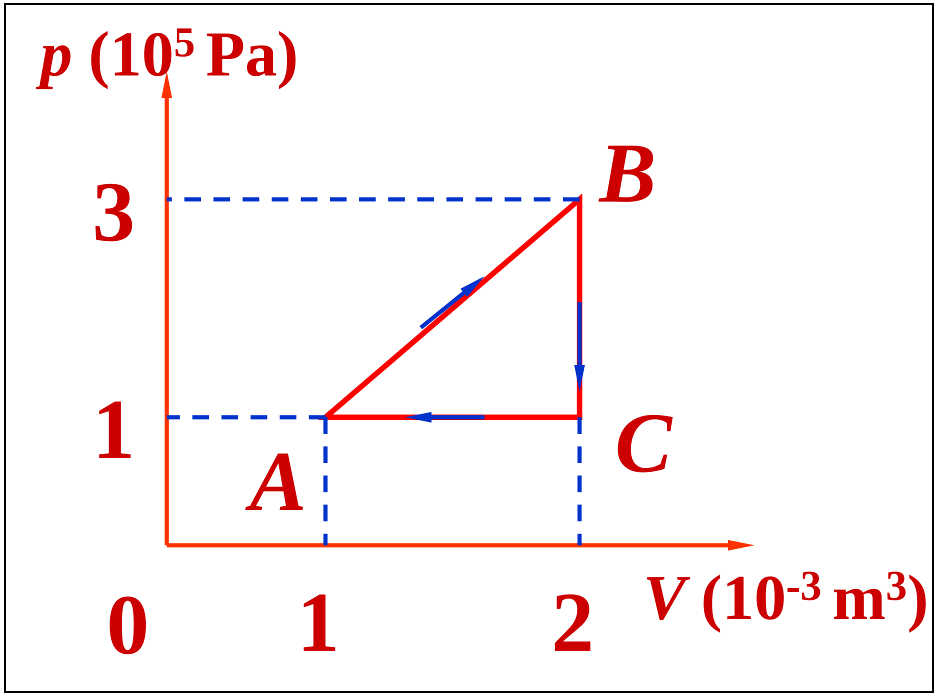
解　A—B

$$W_{AB}=\frac{1}{2}(p_A+p_B)(V_B-V_A)=200\ \mathrm{J}$$

$$\Delta E_{AB}=\nu C_{V,m}(T_B-T_A)$$

$$=\nu\frac{3}{2}R(T_B-T_A)$$

$$=\frac{3}{2}(p_BV_B-p_AV_A)=750\ \mathrm{J}$$



$$Q_{AB}=\Delta E_{AB}+W_{AB}=950\ \mathrm{J}$$

$$Q_{AB}=\nu C_m\Delta T$$

B—C 等容

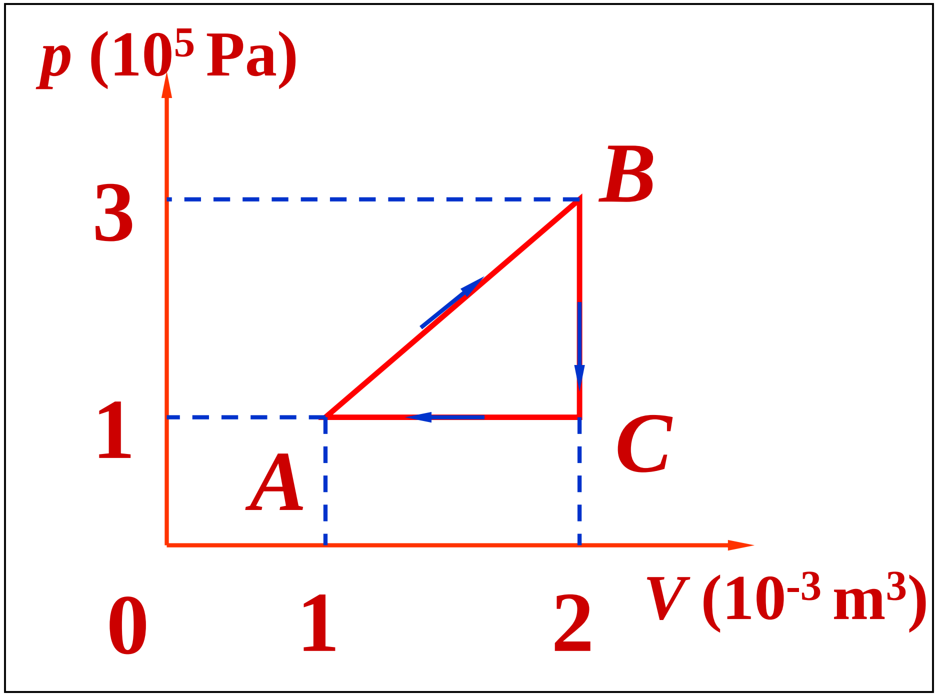
$$W_{BC}=0$$

$$\Delta E_{BC}=\frac{3}{2}(p_C V_C-p_B V_B)$$

$$=-600\ \mathrm{J}$$

$$Q_{BC}=\Delta E_{BC}+W_{BC}$$

$$=-600\ \mathrm{J}$$

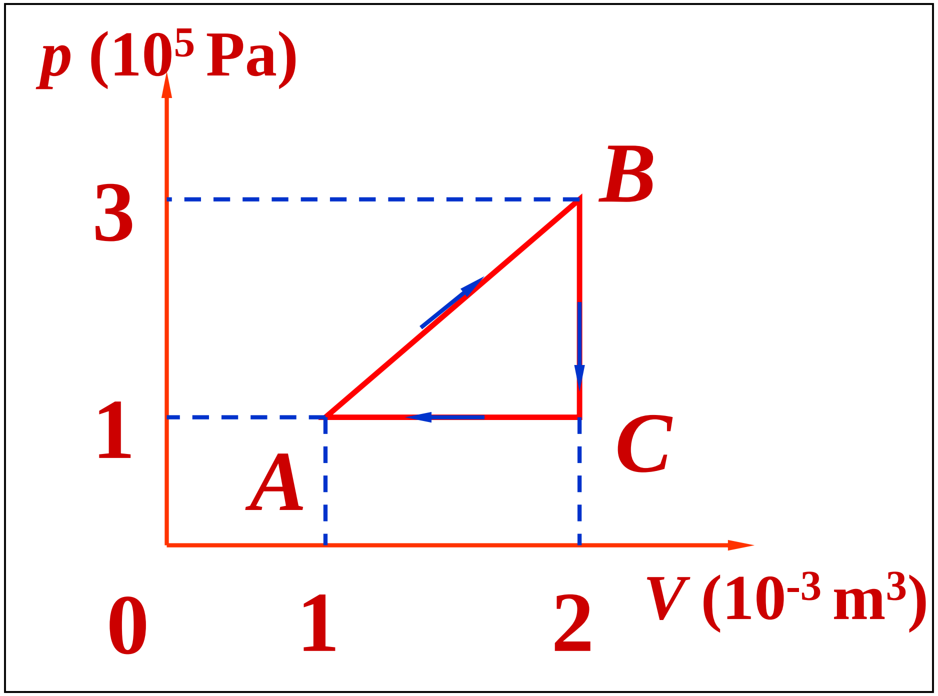


C—*A* 等压

$$W_{CA} = p_A(V_A - V_C) = -100\ \text{J}$$

$$\Delta E_{CA} = \frac{3}{2}(p_A V_A - p_C V_C)$$

$$= -150\ \text{J}$$



$$Q_{CA} = \Delta E_{CA} + W_{CA}$$

$$= -250\ \text{J}$$

$$\eta = \frac{W}{Q_{吸}} = \frac{W}{Q_{AB}}$$

$$= \frac{100}{950} = 10.5\%$$